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Electric field devices for the EDM prototype ring

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Abstract

In the framework of the Physics Beyond Colliders (PBC) study at CERN, the Electric Dipole Moment (EDM) working group is investigating the feasibility of building a storage ring to precisely measure the permanent electric dipole moment of the proton [1]. Protons are stored in an EDM ring at the so-called 'magic' energy of 233 MeV using only electric field elements in order to ensure that spin and momentum vectors precess horizontally at the same rate. For a proton with longitudinal spin, any EDM manifests itself as a measurable vertical spin precession. As a preparation for this main ring, a prototype ring (PTR) is proposed to demonstrate the feasibility of technologies that are not yet operationally confirmed. The PTR is to be small and simple to contain the cost, and will therefore have a circumference of < 100 m. The power supply voltages of the PTR will be limited to 200 kV. The mainly electric field ring will store protons at an energy of 30 MeV for the initial stage and 45 MeV for the final stage (where frozen spin optics will be pursued). This article describes the challenges related to the electric field quadrupoles of the PTR as well as to the injection elements. The feasibility of the each element will be discussed and the outstanding issues are highlighted.

Proposed EDM prototype ring (PTR)

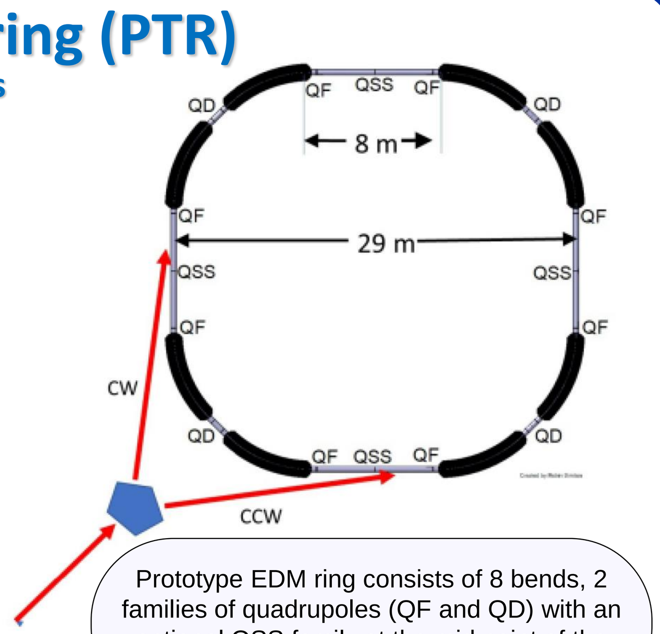
30 MeV and 45 MeV variants

Introduction

The PTR is planned in two stages: a 30 MeV proton ring using electric field dipoles, while the second stage foresees an upgrade to 45 MeV protons using a combined electric and magnetic field dipoles. The aim of this paper is to determine the boundary conditions for the design of the quadrupoles of these rings as well as the assessment of the limitations for the injection elements.

Basic beam parameters for the PTR

	E only	E, B	unit
kinetic energy	30	45	MeV
$\beta = v/c$	0.247	0.299	
γ (kinetic)	1.032	1.048	
momentum	239	294	MeV/c
magnetic rigidity $B\rho$		0.981	T·cm
Electric field only	6.67		MV/m
Electric field E (frozen spin)		7.00	MV/m
Magnetic field B (frozen spin)		0.0327	T

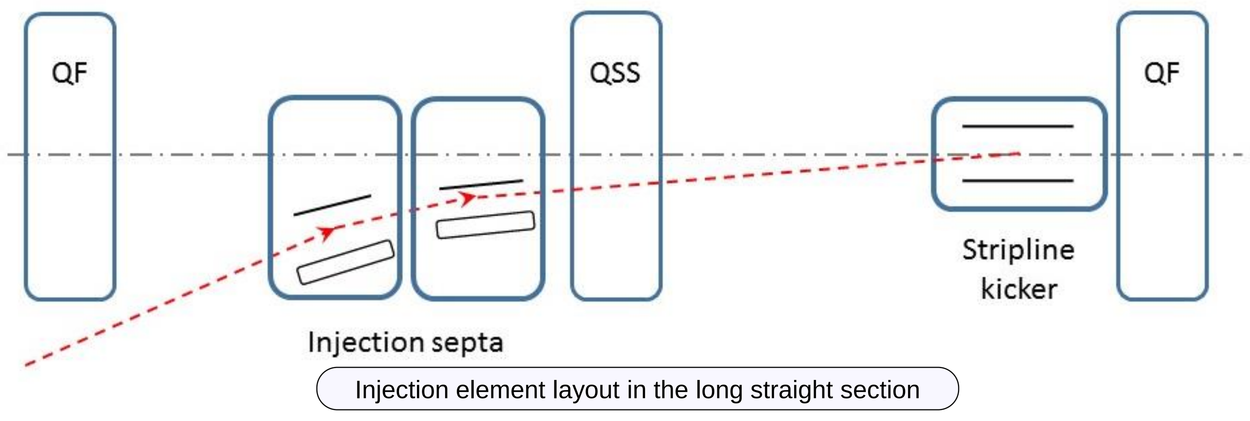


Prototype EDM ring consists of 8 bends, 2 families of quadrupoles (QF and QD) with an optional QSS family at the mid point of the four long straight sections.

Injection

Injection of the two proton beam is foreseen in 2 adjacent straight sections. Since the straight sections are terminated with QF quadrupoles, the overall radial size of this element determines to a great extend the injection angles. The QF design therefore should minimise the horizontal width of the device. To inject, the beam is deflected by an electrostatic septum followed by a fast pulsed separator (fast deflector).

Since the revolution time of the ring is around 1.5 µs and at least 2 bunches need to be injected (clockwise (CW) and counter clockwise (CCW)), a rise and fall time of the kicker is needed of < 250 ns, ideally even 200 ns to allow the injection of 4 bunches in total (2 CW + 2 CCW).



Injection element layout in the long straight section

Quadrupole

Characteristics and mechanical concept

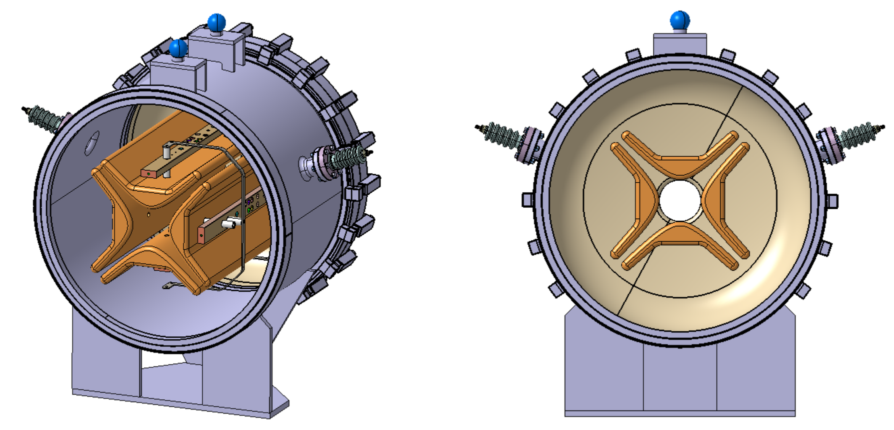
The table shows the principal requirements assumed for the quad in the 45 MeV PTR. A quad design is proposed based on the lattice requirements, respecting the longitudinal physical space available and keeping the horizontal width of the device to a minimum. Ideal hyperbolic shaped electrodes are housed in a ID Ø 500 mm vacuum vessel.

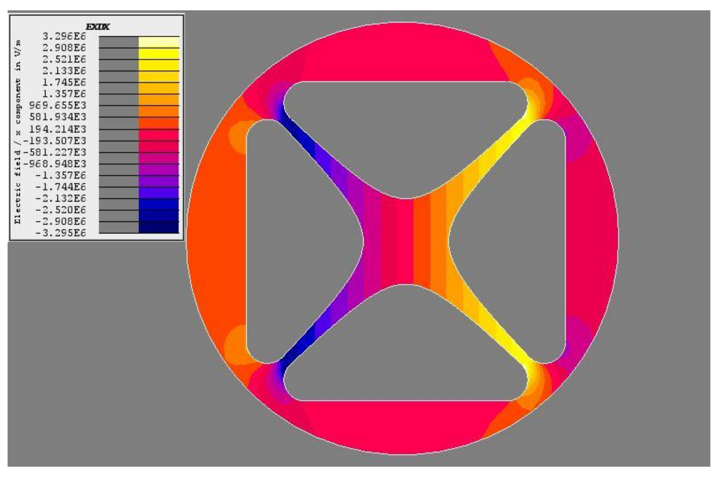
The field precision of the electrode shape was first determined in 2D using Altair Hyperworks Flux2D, and subsequently using Cobham Opera software for the 3D, in a similar approach as was done for the EDM ring elements [3].

The requested stability of the power converters is <10^{-5}.

Principal parameters of electrostatic quadrupoles (QF, QD)

	Lattice assumption	3D design
Physical length [m]	0.8	0.75
Effective length [mm]	0.8	505
Beam aperture [mm]	Ø 80	
Device width [mm]		Ø 600
Electrode length [mm]		500
Field gradient (g) [MV/m²]	25	39.7
Electrode voltage [kV]	± 20	±31.8
Field on pole tips [MV/m]		6.8
Quad focal length [m]	0.11	
Field gradient homogeneity in GFR Ø 20 mm	1.10^{-4}	1.10^{-3}

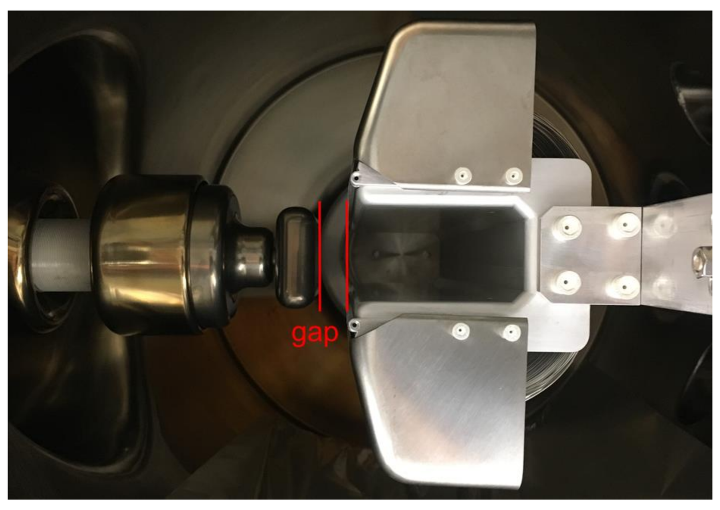




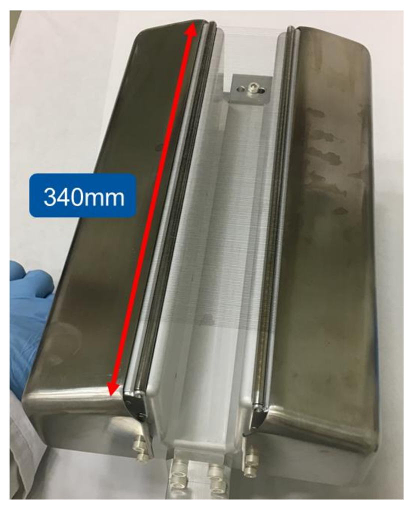
Septum CNT wire anode tests

Low Z septum material for septum anode

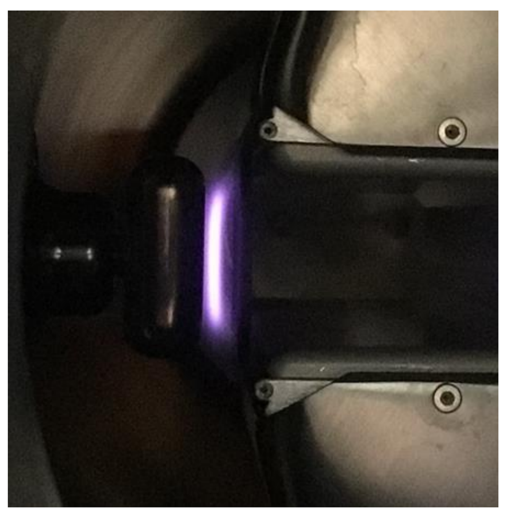
Septum anode material is commonly Mo foil, W26Re wires. Albeit very robust, these high Z materials scatter particles lost on the septum further down the accelerator. As such, the septum but also equipment further down stream is activated. To reduce scattering, hence residual activation, low Z materials would be preferable. Tests are being done to assess the suitability of Carbon Nano Tube (CNT) wires as anode material.



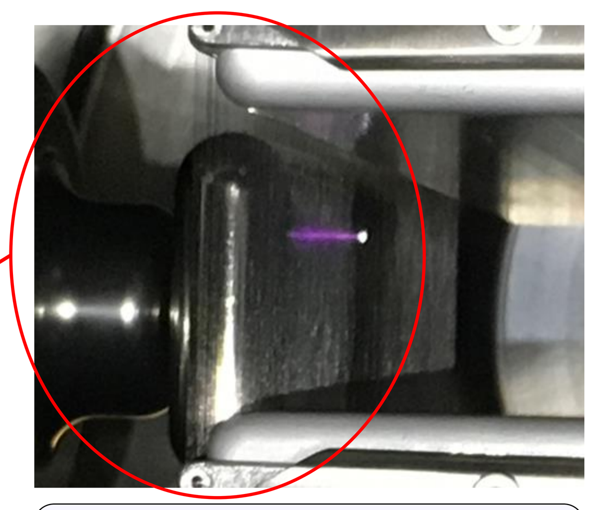
Septum test set-up: left Ti cathode, right Al support of CNT wire septum anode.



Septum anode using CNT wires



Argon glow discharge conditioning



Inverse polarity conditioning under Argon

Wire, saw sparking, but not blackened

Wire, saw sparking, blackened

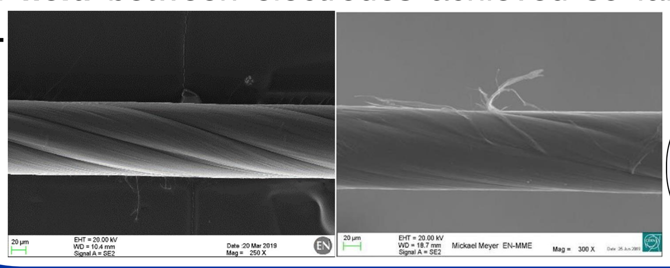
Wire, no sparking, not blackened

Conditioning reveals to be very difficult under vacuum. Large DC (dark?) currents appear immediately after the first spark; this current cannot be recovered.

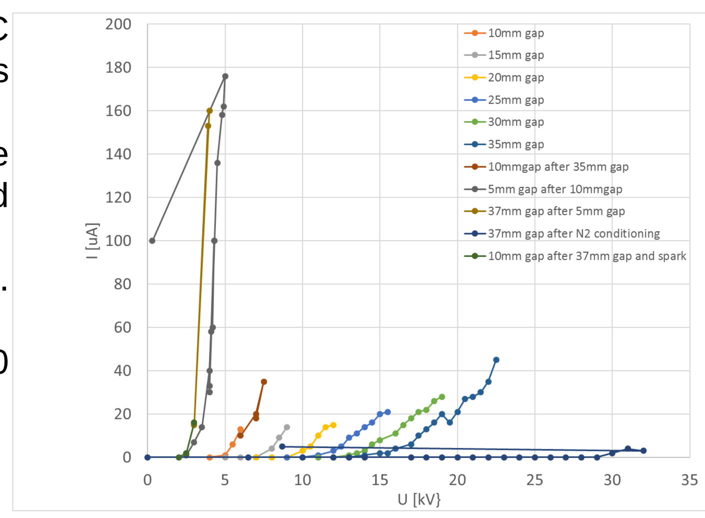
Conditioning (sparking) under nitrogen at atmospheric pressure is efficient, and remove any DC (dark) current that was observed under vacuum

Conditioning under argon @ 10 mbar seems to polish the wires. However no improved voltage hold-off capacity observed yet.

Max. field between electrodes achieved so far: 3 MV/m (gap 10 mm).



CNT wire, before (left) and after (right) mounting on anode support



Conditioning under vacuum

Injection equipment

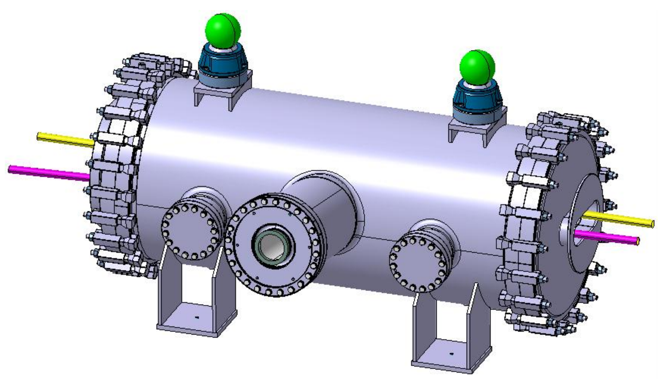
Concept and characteristics

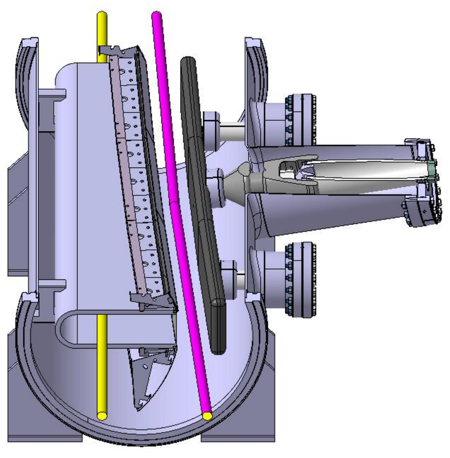
The septum and its (anode) support need to be curved to limit the gap to 70 mm wide, while displacing the beam by 18 mm. The septum can be made of bent or segmented 1 mm thick titanium sheet. Alternatively wires can be used to obtain a thinner septum. Ideally a low Z material could be used to keep radiation activation as low as possible. By keeping the gap limited to 78 mm the operational voltage required remains below 210 kV. The cathode can be made of stainless steel.

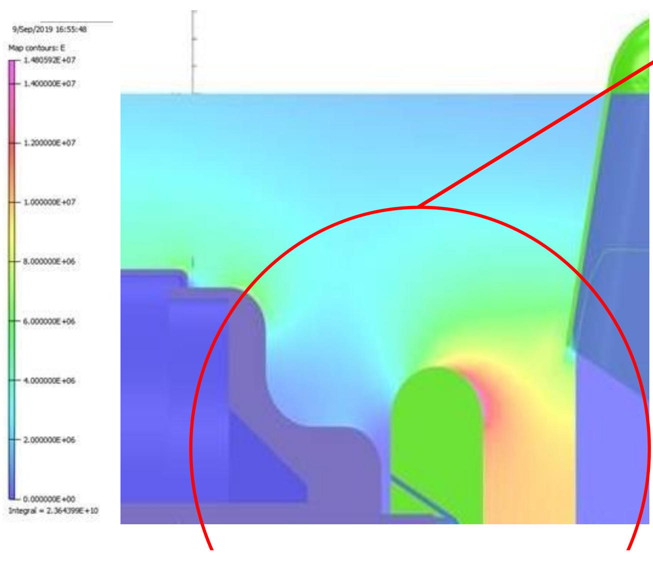
The septum will be supplied with DC voltage and needs to be conditioned to above 250 kV prior to operation. The septum and electrode gap width will be fixed, potentially making conditioning more delicate, but this reduces the complexity of the device, hence it's cost significantly.

Principal parameters of injection elements for 45 MeV protons

	Septum	Stripline kicker
Physical length [mm]	1200	1200
Tank diameter [mm]	OD	ID 200
Effective length [mm]	1000	1000
Deflection angle [mrad]	30	17.6
Gap width (H x V) [mm²]	70 x 80	75 x 75
Electric field [MV/m]	2.6	0.8
Magnetic field [mT]	0	3.5
Voltage on the electrodes [kV]	206	30
GFR H × V [mm²]	40 × 30	30 × 30
Field homogeneity in GFR		10^{-2}
Characteristic impedance [Ω)		50
Current [A]	0	600
Radius of curvature electrodes [m]	33	//
T_{rise} and T_{fall} [ns]	DC	200 – 250
Capacitance between electrodes [pF]	38	66.5

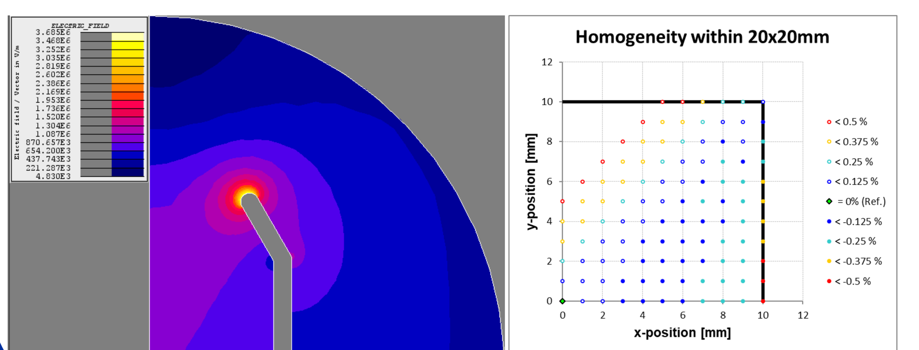




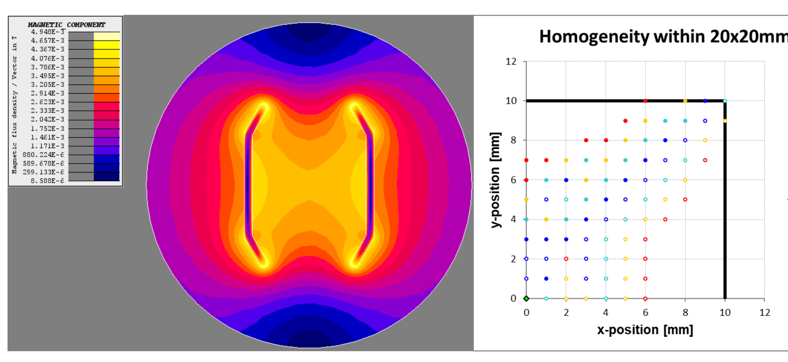


The stripline kicker gap width is taking into account the beam sagitta using straight electrodes. Two pulse generators will be connected to the kicker, each powering an electrode. Due to the fast rise time and current, the most suitable power generator topology will be of the inductive adder type [2].

The characteristic impedance of the stripline kicker (50 Ω) was chosen as a starting point to be compatible with the inductive adder generator. However the detailed design of the actual kicker is still to be finalised which may lead to small changes in the electrode shape and tank inner diameter.



Electric field profile and homogeneity of the stripline kicker.



Magnetic field profile and homogeneity of the stripline kicker

Conclusions

To inject the polarised proton beam, the long straight sections and large beam aperture required impose relatively high voltages on the injection elements. The QF quadrupoles are designed to minimise their transverse footprint, as to minimise the required kick of the injection elements.

Using a stripline kicker (with both an electric field and a magnetic field component) the beam can be injected in the baseline lattice.

Tests with CNT wire as septum anode indicate that for the time being modest fields of ~ 3 MV/m can only be obtained. Conditioning with this type of anode is very difficult. Conditioning under nitrogen at atmospheric pressure seems to be an effective preparation to achieve the highest fields under vacuum. Conditioning under argon with partial pressures in the region of 10 mbar seems to improve the wire surface finish (polishing effect?). This effect is for the time being only observed on the part of the anode, which may explain why no subsequent improved HV performance has been observed as yet.

References

[1] M. Lamont et al., " Feasibility study for a storage ring to search for Electric Diploe Moments of charge particles", CERN yellow report to be published 2019

[2] M. Barnes et al., "Design of an inductive adder for the FCC injection kicker pulse generator", IPAC'17, Copenhagen, Denmark

[3] J. Borburgh et al., "Challenges for the electric field devices for a CERN proton EDM storage ring, proc. ISDEIV 2018, Greifswald, Germany